UNITED STATES PATENT APPLICATION

of

CHEE WEI WONG

STEVEN G. JOHNSON

GEORGE BARBASTATHIS

and

SANG-GOOK KIM

for

DYNAMICALLY TUNABLE PHOTONIC BANDGAP MICROCAVITY WAVEGUIDES
VIA MECHANICAL LATTICE CONTROL

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PRIORITY INFORMATION

5   This application claims priority from provisional application Ser. No. 60/395,926 filed July 15, 2002, provisional application Ser. No. 60/467,854 filed on May 5, 2003, and is a continuation-in-part of application Ser. No. Unknown filed July 14, 2003 (Express Mail No. EV271853767US), entitled "Reconfigurable Microphotonics Devices Via Deformable Membrane Platforms," by common assignee.

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BACKGROUND OF THE INVENTION

The invention relates to the field of microphotonics, and in particular to tuning a photonic bandgap in a microcavity waveguide structure via mechanical deformation.

The vast majority of microphotonic devices possess a wide spectrum of 15   applications. Most of these devices are static devices, where reconfiguration is not possible after device fabrication. To achieve tuning of microphotonic devices, the electro-optic effect, the charge-carrier effect (via temperature and / or doping), and the liquid crystal tuning methods have been used. There is a need in the art for a method of tuning on the order of 13 nm for resonant frequency centered at 1.552 μm for the 40 nm 20   wide C-band in optical telecommunications. Moreover, there is a need also to allow tunability and control in silicon microphotonic devices.

SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided a photonic bandgap microcavity. The microcavity includes a membrane structure that can experience strain. A photonic bandgap waveguide element is formed on the membrane structure having a

5   defect so that when the membrane structure is strained, the photonic bandgap waveguide element is tuned to a selective amount.

According to another aspect of the invention, there is provided a method of forming a photonic bandgap microcavity. The method includes providing a membrane structure that can experience strain. The method also includes forming a photonic

10   bandgap waveguide element on the membrane structure having a defect so that when the membrane structure is strained, the photonic bandgap waveguide element is tuned to a selective amount.

BRIEF DESCRIPTION OF THE DRAWINGS

15   FIG. 1A is a schematic block diagram illustrating the concept of strain-tuning photonic bandgap microcavity waveguides; FIG. 1B is an expanded view of FIG. 1A;

FIG. 2 is a two-dimensional representation of a three-dimensional finite-difference time-domain computation of the microcavity waveguide;

FIG. 3 is a schematic diagram demonstrating strain on the microcavity

20   waveguide;

FIGs. 4A-4C are schematic block diagrams of other configurations of tunable photonic waveguides used in accordance with the invention; and

FIG. 5 is a flowchart demonstrating the steps used in fabricating a tunable photonic bandgap microcavity waveguide.

DETAILED DESCRIPTION OF THE INVENTION

5   The invention uses a new concept of tuning a photonic bandgap in a microcavity waveguide structure via mechanical deformation. A photonic crystal structure is superimposed onto a thin sub-micron deformable membrane, and controlled deformation of the membrane will allow the geometric lattice structure to be tuned via mechanical strain. Membrane deformation is made possible with the use of thin-film piezoelectric

10   actuators. With the controlled deformation, optical properties of the microcavity waveguide, such as resonance in the bandgap of the transmission spectra, the size of the bandgap, the quality factor Q of a cavity, and other optical properties can be tuned. Fine control of the mechanical strain, through the piezoelectric actuators, will allow fine-tuning of these optical properties. The inventive device can be used in integrated

15   photonic chip architectures and devices, such as low-threshold microlasers, filters, signal routers, and the like.

       Moreover, this invention will also allow for dynamic tuning of these properties, either in part of the device function or in response to external disturbances. Real-time reconfigurability of the photonic crystals can be achieved. The range of tunability is on

20   the same order of magnitude with electro-optic and charge-carrier tunability effects in compound semiconductor materials.

       In addition, mechanical strain-tuning provides tunability to silicon microphotonic devices, given the absence of electro-optic and charge-carrier effects in silicon. Although

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thermal tuning provides an alternative for tunability in silicon microphotonics, it requires high power consumption, has poor spatial localization of the tunability, and has a relatively slow response time compared to mechanical strain-tuning with piezoelectric actuators.

5   A single mode photonic crystal waveguide 2 is used to both confine light along two dimensions and maintain a preferred polarization of the guided mode, as shown in FIG. 1A. The introduction of a periodic array of holes 10, in a 1-dimensional photonic crystal waveguide 2, into the waveguide limits the wavevector to π/a, where a is the lattice constant, or spatial period, of the array of holes 10, as shown in FIG. 1B. This

10   allowable range of wavevectors is similar to the Brillouin zone used in solid-state physics. In addition, the 1-dimensional photonic crystal waveguide 2 has the effect of folding the dispersion relation of the strip waveguide and of splitting the lowest-order mode. The splitting at the Brillouin zone edge produces a bandgap, the size of which is strongly affected by the dielectric contrast.

15   The addition of a defect 8 by creating a break in the periodicity in the 1-dimensional photonic crystal waveguide 2 allows a state to propagate in the bandgap. This state is analogous to a defect or impurity state in a semiconductor that forms a level within the semiconductor bandgap. Conceptually, this is also analogous to 1-dimensional Fabry-Perot resonators, although it has a coplanar geometry and the ability to give rise to

20   strong field confinement. The break in the periodicity leads to a defect state that is localized in real space and therefore extended in the wavevector space.

        Control of the periodicity of defect 8, with length a_d, leads to tuning of the resonant frequency as a tunable resonator or filter. While electro-optic and thermal

tuning could be used to control the optical path length or the break in periodicity, mechanical tuning is preferable due to reasons described earlier.

The thin-film membrane 6, on the order of 200 - 400 nm in thickness, is mechanically-strained through the thin-film piezoelectric actuators 4, such as lead

5   zirconate titanate (PZT), poly-vinylidene fluoride (PVDF), zinc oxide or aluminum nitride. The high power density, which is on the order of 1000 W/kg, of the PZT actuators provides a predicted and experimentally measured strain of approximately 0.2% on the deformable membrane. The specific mechanical tuning range depends on the design, actual fabrication, and material selection. With super-imposing the photonic

10   crystal waveguide 2, both the lattice constant and the ratio of defect length over the lattice constant are changed.

FIG. 2 shows an exemplary two-dimension slice of the $E_{x,real}$ field distribution, where x is the direction along the waveguide 2 described in FIGs. 1A and 1B. The total quality factor Q, where Q is the fractional width at half-maximum of the resonance

15   transmission response, of 180 is derived based on the information shown in FIG. 2. Superimposed on the field distribution are the locations of the dielectric boundaries, for a Si waveguide with air holes. The high dielectric contrast, between air and silicon or silicon oxide and silicon, leads to strong mode localization, permitting high-density packing of the microcavity waveguides. The maximum amount of deformation will be

20   limited by the strain limit of the membrane or the actuators. For a PZT piezoelectric actuator, the strain limit could reach up to 0.1%, without mechanical amplification. The ratio of the PZT actuator length to membrane length serves as an amplification factor. The strain limit of the photonic crystal material is highly dependent on the surface

roughness of the material; a Si material with surface roughness below 20 nm (in order for low optical scattering in the waveguide) has fracture stresses above order of 1 GPa, corresponding to a strain limit of 0.7%. While the strain limit is dependent on the detailed microfabrication process and expressed as a probability distribution function

5   through Weibull statistics, a strain of 0.2 to 0.3% is a safe estimate.

FIG. 3 shows a finite-element model of the microcavity waveguide under mechanical strain. The local strain at the hole region between two hole centers is larger than that at the defect region, and approximately 1.5 times the strain in the defect. The strain in the defect is on the order of the external applied strain. This factor of 1.5

10   contributes added tunability to the resonant frequency, since the a_d/a ratio is further changed under mechanical strain. The a_d/a ratio affects the frequency of the resonant mode within the photonic bandgap; a larger a_d/a ratio leads to a lower resonant frequency for all other dimensions kept the same.

As the expected tunability range is on the order of 1%, direct numerical FDTD

15   simulation to capture the effects would require a very fine-mesh and would be computationally intensive. Instead, perturbation theory of Maxwell's equation provides an elegant method to describe the tunability, overcoming the issues of numerical accuracy. Moreover, perturbation theory captures shape-profile distortions in the periodic structures, which in our scenario is the elliptical profile of the circular holes

20   under deformation. The elliptical displacement profile is derived analytically, beginning from the stress mechanics of the hole-in-a-plate situation. The change in the resonant frequency with respect to an applied external perturbation, $d\omega/d\alpha$, can be described as follows:

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$$\frac{d\omega}{d\alpha} = -\frac{\omega^{(0)}}{2} \frac{< E^{(0)} |\frac{d\varepsilon}{d\alpha}| E^{(0)} >}{< E^{(0)} |\varepsilon| E^{(0)} >} \qquad \text{Eq. 1}$$

where $\omega^{(o)}$ is the resonant frequency before strain-deformation, $E^{(o)}$ the electric field distribution before strain-deformation, α the perturbation parameter (external applied stress in this scenario) and ε the permittivity. Specifically, the top integral, summed over the dielectric boundary area A, can be expressed as:

$$< E^{(0)} |\frac{d\varepsilon}{d\alpha}| E^{(0)} > = \int dA \frac{dh}{d\alpha} [\ \Delta\varepsilon_{12} |E_{\parallel}^{(0)}|^2 - \Delta\varepsilon_{12}^{-1}|D_{\perp}^{(0)}|^2\ ] \qquad \text{Eq. 2}$$

where $dh/d\alpha$ is the change in dielectric boundary given the applied external stress, $E_{\parallel}$ the electric field parallel to the boundary, $D_{\perp}$ the electric displacement perpendicular to the boundary, $\Delta\varepsilon_{12}$ the difference of permittivity ε_1 and ε_2 , and $\Delta\varepsilon_{12}^{-1}$ the difference in the reciprocal of the permittivities.

The bottom integral, $< E^{(0)} |\varepsilon| E^{(0)} >$, is the volume integral of the electric field in the structure of interest. With the unperturbed FDTD results, the perturbation computations are performed, using analytical results of the elliptical nature under stress deformation to derive $dh/d\alpha$, and employing interpolation between the discretized FDTD mesh to obtain $E_{\parallel}$ and $D_{\perp}$. The results show a 1.41% tunability in the resonance peak with 0.5% externally applied tensile strain. The tuning is linear with response to the applied strain, and has a 13 nm shift in resonance at 0.3% externally applied strain for C-band telecommunication wavelengths.

Specifically, confinement of strain at solely the defect cavity (changing only a_d) results in a +0.58% change in resonance wavelength for +0.5% change in a_d. Secondly,

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increasing only the lattice constant a, however, has two effects: (1) an increase in the geometric size and hence increasing the operating wavelength and shifting the bandgap (in terms of wavelengths) upwards, (2) a decrease in the a_d/a ratio and hence leading to a decrease in the resonance wavelength within the bandgap. The net result of all these

5 effects is found through computation and has a +0.8215 % change in resonance wavelength for a +0.5% change in lattice constant a.

Finally, the effects of ellipticity are included and found to decrease the resonance wavelength. The complete computation, including strain at defect cavity, strain at lattice constant and ellipticity of holes, shows a +1.41% change in resonance wavelength for a

10 +0.5% mechanical tensile strain.

Other configurations of tunable photonic crystal waveguides are illustrated in FIGs. 4A-4C. FIG. 4A shows two-dimensional photonic crystal 14 with ridge waveguides 16. FIG. 4B shows a two-dimensional photonic crystal 18 with tapered input 20 and output 22 coupling waveguides. FIG. 4C shows an one-dimensional photonic

15 crystal waveguide 24 for polarization in the vertical direction (Transverse Magnetic modes).

FIG. 5 shows a flowchart of steps needed to fabricate the inventive microcavity. Firstly, precise patterning of a photonic crystal structure via X-ray lithography with an electron-beam written mask is performed on a Unibond SOI wafer (step 26). A

20 protective layer, such as SiN_x, is deposited on the photonic crystal (step 28). A Pt/Ti layer is CVDed and lift-off patterned to form the bottom electrode for the PZT actuator (step 30). The PZT actuator thin-film is Sol-gel spin-on, annealed and wet-etched (step 32). Another Pt/Ti layer is CVDed and lift-off patterned to form the top electrode for the

PZT actuator (step 34). The top and bottom Pt/Ti electrodes provide a differential voltage to the thin-film PZT. A handle wafer is mounted to protect front-side of the SOI wafer (step 36). Backside Deep Reactive Ion Etching is used to remove bulk Si substrate (step 38). The SiO_2 membrane layer is patterned via Reactive Ion Etching to free the membrane (step 40). The handle wafer is removed (step 42).

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is: